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SIZING RIPRAP FOR THE PROTECTION OF APPROACH EMBANKMENTS & SPUR DIKES AND LIMITING THE DEPTH OF SCOUR AT BRIDGE PIERS & ABUTMENTS

Volume I: Literature Review & Arizona Case Histories

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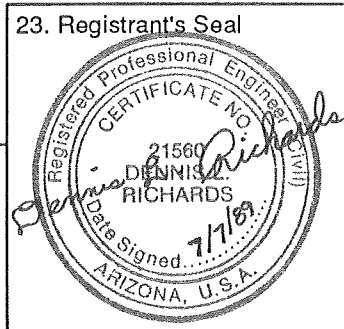
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16. Abstract <p>This report presents a review of published literature on riprap design technology and examines Arizona case histories of riprap performance. The literature review grouped the factors affecting riprap design into hierarchical categories relative to scale. The four factors identified include: riprap properties, site characteristics, hydraulic and sediment transport conditions, and river response. Eleven case histories from documentation supplied by the Arizona Department of Transportation (ADOT) and the U.S. Department of Agriculture, Soil Conservation Service (SCS) are examined. The review of Arizona case histories is intended to provide the basis for understanding the dominant river processes associated with riprap protection measures. The literature review and case histories indicate a set of design requirements to be considered when designing riprap revetment.</p> <p>Design Procedure, Volume 2</p>			
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LIST OF SYMBOLS

Symbol	Description
C	Froude Number coefficient for relative depth
C_s	Froude Number coefficient relating Shields parameter to the relative depth
d	average depth of flow
D_{15}	rock size which only 15% is finer by weight
D_{20}	rock size which only 20% is finer by weight
D_{30}	rock size which 30% is finer by weight
D_{35}	rock size which only 35% is finer by weight
D_{50}	median rock size
D_{100}	rock size which 100% is finer by weight
D_m	representative riprap grain size
D_{max}	maximum riprap size specified in the design gradation (D_{100})
F	Froude Number, V_a / \sqrt{gd}
g	gravitational constant, 32.2 ft/sec ²
G	gradation coefficient, $1/2[D_{84}/D_{50} + D_{50}/D_{16}]$
K	tractive force ratio
r	the radius of curvature
R	hydraulic radius
S	slope of the energy grade line
V_a	average velocity
w	topwidth of the channel
W_{100}	rock weight of gradation which 100% are lighter
W_{15}	rock weight of gradation which 15% are lighter
W_{50}	rock weight of gradation which 50% are lighter
γ	unit weight of water, 62.4 lbs/ft ³
τ	average boundary shear stress
τ_{cb}	critical shear stress on the bed of the channel
τ_{cs}	critical shear stress on the side-slope of the channel
θ	angle of repose of the material that forms the side-slope
ϕ	channel side slope angle

I. INTRODUCTION

This report presents the results and findings of Task One of Research Project No. HPR-PL-1(31) Item 260, Sizing Riprap for the Protection of Approach Embankments and Spur Dikes and Limiting the Depth of Scour at Bridge Piers and Abutments. The objective of this study task was to perform a literature search, to identify the research that has been conducted on riprap protection, with an emphasis on research pertaining to conditions in Arizona. In formulating the approach for the study, it was determined that the initial review phase should address not only published research, but should also seek out case histories of riprap performance. Examination of Arizona case histories is intended to provide the basis for understanding the dominant river processes associated with riprap protection measures. It was felt that combining published research on riprap performance with information from case histories would best allow the determination of riprap design requirements for conditions characteristic of Arizona.

Case histories were sought from a number of Federal, State, County and local agencies during Task One. The agencies contacted expressed a willingness to share design experience and practice. All districts of the Arizona Department of Transportation (ADOT) were contacted for information on their knowledge of riprap problems. An extensive review of reports, construction plans, and bridge inspection records was conducted at ADOT headquarters with the assistance of the hydraulics and structures sections staff. We found ADOT's evaluation of deficiencies at bridge structures related to scour to be a very pertinent source of case histories. Over the past six years, the Scour Team has evaluated scour conditions at over one hundred bridge sites, and has prepared a substantial number of reports, and initiated projects to construct countermeasures.

Contact with Federal agencies included: The Corps of Engineers, Bureau of Reclamation and Soil conservation Service. Discussions with the staff at these agencies lead us to the conclusion that the Soil Conservation Service could supply the most pertinent case histories. Background on the type of information available from each of these federal agencies contacted is discussed later in the report. The Central Arizona Water Conservancy District was contacted and the Salt River Project. The design problems encountered by these agencies were sufficiently different from the focus of

this study that they were not pursued. The Pima County Department of Transportation and Flood Control District and the Flood Control District of Maricopa County were contacted. Neither of these agencies uses riprap to any great extent; soil cement and gabions are preferred for most projects. The Cities of Phoenix and Tucson were contacted and as with their counterparts at the county level, soil cement is the preferred method of stabilizing river banks.

Eleven case histories were developed from documentation supplied by ADOT and the SCS. Eight of the ten case histories are from ADOT projects and cover countermeasures installed at bridge waterways. Two SCS projects are presented as case histories.

The literature search concentrated on four categories of channel stability: riprap characteristics, hydraulic and sediment transport conditions, site characteristics, and river response. The review provides an overview of research pertinent to the study.

The literature review and case histories point to a set of design requirements that should be considered for riprap protection. The second volume of this report addresses methodologies currently available to meet these design requirements. The limitations of these methods and particularly their applicability to conditions observed in Arizona were evaluated and an interim design procedure is recommended.

II. REVIEW OF LITERATURE ON RIPRAP DESIGN TECHNOLOGY

2.1 Overview of Literature on Riprap Design Technology

The design of riprap protection measures involves assessment of a number of factors associated with the river environment, the bridge site, and the quality of the riprap material. As can be seen from the case histories presented in Chapter 4, most bridge sites are affected by a combination of these factors. There is a body of research that addresses individual aspects of riprap design, where data on riprap performance has been gathered from laboratory studies. Another body of research has addressed field performance of riprap installations. Field study requires a longer period of investigation, and physical measurements are more difficult to accurately obtain, and therefore, are less commonly reported in the literature.

The literature reviewed for this study has been grouped into the following four categories:

Riprap Properties:

Size, gradation, shape, layer thickness, density, rock durability, and bedding requirements.

Site Characteristics:

Structure location (encroachment length and skew), channel alignment and shape, and bank side-slopes.

Hydraulic and Sediment Transport Conditions:

Incipient motion, boundary shear stress, local scour, general aggradation/degradation, bed forms.

River Response:

Change in channel area, topwidth, depth, gradient, bed-material gradation, and sinuosity in response to flood flows.

This grouping of factors in riprap design is hierarchical in scale, that is one set of factors addresses processes that are on the order of a few feet, while others may be on the order of tens of miles. Riprap characteristics involve the population of riprap particles, which are each less than a few feet in size. Site characteristics are concerned with a scale on the order of two to three times the crossing length, or typically on the order of a few hundred feet. Hydraulic and sediment transport conditions are typically evaluated over a reach length, upstream and downstream of the

site, of a few thousand feet. River response is typically evaluated at the basin level on the scale of several tens of miles. This distinction in scale is not always easily perceived, but both large scale and small scale factors can lead to design deficiencies for a project.

2.2 Riprap Characteristics

The physical characteristics of the rock particles that make up riprap protection most often cited in specifications include: a characteristic size, gradation, layer thickness, shape, specific gravity, durability, and filter requirements. Research on these basic physical characteristics has concentrated primarily on size, gradation, shape, and layer thickness.

Characteristic Size

The characteristic riprap size is generally taken as the diameter of the median of the gradation by weight or the D_{50} . General references on riprap design, such as Sediment Transport Technology (Simons and Senturk (1977)), present a number of design procedures, the majority of which characterize the riprap by the D_{50} size. In the training and design manual, Highways in the River Environment, (Richardson, et al., 1987), it is noted that riprap may armor, "...leaving a layer of large rock sizes which cannot be transported under the given flow conditions. Thus, the size of rock representative of the stability of the riprap is determined by the larger sizes of rock. The representative grain size D_m for riprap is larger than the median rock size D_{50} ." Using the recommended gradation in Highways in the River Environment, (page V-26,27) where the $D_{20} = 1/2 D_{50}$ and $D_{100} = 2 D_{50}$, an effective grain size of $1.25 D_{50}$ is computed which corresponds to the D_{65} riprap size. The manual goes on to note that, "[T]he weight of a bed-material particle is important to the stability of the particle. Thus, it is more meaningful to compute the representative particle size based on weight of the particle than on its diameter." Mahmood (1973), found that the distribution of bed-material properties could be described by a log-normal probability distribution. The representative size of the bed material based on the weight of the particles can be described as a function of the gradation coefficient (Mahmood, 1973):

$$D_m = D_{50} \exp \left[\frac{3}{2} (\ln G)^2 \right]$$

where

D_m = the representative grain size,

D_{50} = median rock size, and

$G = 1/2 [D_{84}/D_{50} + D_{50}/D_{16}]$.

which is always greater than one for a non-uniform grain size distribution.

More recently, data gathered by Maynard (1986) indicates that the D_{50} may not characteristic size riprap stability. He found that for the range of gradations tested by the Corps of Engineers Waterways Experiment Station, that incipient failure of riprap could be more reliably evaluated using the D_{30} size. In support of this finding, Maynard sites work on bed armoring by Shen and Lu (1983) and the Einstein bed-load function (1950) which uses D_{30} and D_{35} as characteristic sizes, respectively.

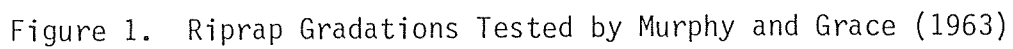
Gradation

The gradation of riprap sizes is of considerable importance both in terms of the stability and in preventing leaching of the base material. Anderson (1970) noted that with a graded distribution of riprap as the thickness is increased, the interstices left by large particles are filled by smaller particles. As the layer thickness or the variations in particle sizes increases, the number of direct paths to the base material decreases. When boundary shear stress at the riprap surface is less than the smaller sizes in the distributions, the stability of the riprap is maintained. A riprap gradation with a large variation in particle sizes was observed by Anderson to experience erosion of the smaller sizes, as boundary shear increased. In riprap gradations with less variation in particle size, the smaller particles tended to be sheltered by larger particles and remained stable as boundary shear stress increased. Gradations tested by Anderson ranged from uniform to $G = 2.0$. Highways in the River Environment recommends using the following U.S. Army Corps of Engineers (1982) criteria for establishing gradation limits for riprap:

- . The lower limit of D_{50} stone should not be less than the size of stone required to withstand the design shear forces.
- . The upper limit of D_{50} stone should not exceed five times the lower limit of D_{50} stone, the size which can be obtained economically from the quarry, or the size that satisfies layer thickness requirements.
- . The lower limit of D_{100} stone should not be less than two times the lower limit of D_{50} stone.
- . The upper limit of D_{100} stone should not exceed five times the lower limit of D_{50} stone, the size which can be obtained economically from the quarry, or the size that satisfies layer thickness requirements.
- . The lower limit D_{15} stone should not be less than one sixteenth the upper limit of D_{100} stone.
- . The upper limit of D_{15} stone should not be less than the upper limit of the filter material.
- . The bulk volume of stone lighter than the D_{15} stone should not exceed the volume of voids in the structure without this lighter stone.

Murphy and Grave (1963) tested various rock sizes and gradations in conjunction with protection of overflow dikes. Two gradations, A and A1 (Figure 1), failed under the same conditions although gradation A had maximum particles 36 inches in diameter as opposed to 24 inches for gradation A1. Both gradations had a median diameter of 16 inches. The two gradations B and C, failed under the same conditions. The greater variation in particle sizes in the C gradation resulted in a maximum size of 24 inches compared to 16 inches for the B gradation. However, only 15 percent of the B gradation was less than half the D_{50} , compared to 30 percent for the C gradation. In the model test, it was found that riprap failure occurred by removal of smaller particles, resulting in the dislodgement of larger particles. Murphy and Grace concluded that stones larger than some critical size (approximately D_{65} in their tests), do not increase riprap stability.

Searcy (1967) proposed three classes of riprap for use in riprap protection at highway bridges and proposed a single gradation. The gradation is referenced to the median size, D_{50} .



<u>Size of Stone</u>	<u>Percent of total weight smaller than the given size</u>
3D ₅₀	100
2D ₅₀	80
1D ₅₀	50
0.1D ₅₀	10

Searcy based this gradation on findings by Murphy and Grace, but realized that unless a large quantity of riprap was to be installed, that it might prove undesirable to specify more than a single gradation. The Searcy gradation was intended to accommodate actual field conditions.

In the Corps of Engineers design manual, "Hydraulic Design of Flood Control Channels" EM-1601, (1970), a set of criteria was presented for establishing gradation limits. The criteria result in a range of stone weights for each fraction of the gradation rather than a single gradation curve. Ranges are determined for the D₁₀₀, D₅₀, and D₁₅ size fractions, where the lower limit for D₅₀ is set to meet boundary shear stress conditions, and the upper limit is set based on an economically feasible quarry size. The limits for the other two size fractions are set as follows:

$$W_{100L} > 2 W_{50L}$$

$$W_{100U} < 5 W_{50L}$$

$$W_{15L} > 1/16 W_{100U}$$

$$W_{15U} < W_{50U}$$

where W is the stone weight and the numerical subscript refers to the percent lighter by weight, and "L" and "U" denoting the upper and lower limit of the range.

Maynard (1986) reports on laboratory tests conducted by the Corps on riprap and indicates that for gradations having D₈₅/D₁₅ less than 4.6, a single incipient failure criteria could be developed. As mentioned earlier, Maynard found the D₃₀ size to be characteristic of riprap stability.

To make the specification of riprap gradation somewhat easier, the Corps issued Engineer Technical Letter (ETL) No. 1110-2-120 that provides additional guidance for riprap channel protection. This ETL provides a series of tables that allow gradation limits to be determined based on physical characteristics of the riprap.

Blodgett and McConaughy (1986) compare stone gradations specified in different design procedures. Figure 2 presents their comparison and includes Oregon and California specifications.

Shape

Another important property for riprap stability is riprap particle shape. Angular, well-proportioned rock particles tend to interlock and form a more stable mass than rounded rock shapes. Lane (1955) observed the angle of repose of material on stock piles and noted that the angle of repose increased for angular and crushed rock over round rock. Lane constructed a chart showing the angle of repose as a function of shape and median riprap diameter. Simons (1957) developed a similar set of curves based on his observations of the angle of repose for coarse, noncohesive material. The importance of the angle of repose in the stability of riprap was shown theoretically by Carter, Carlson and Lane (1953) which they expressed as the tractive force ratio, K,

$$K = \frac{\tau_{cs}}{\tau_{cb}} = 1 - \frac{\sin^2 \phi}{\sin^2 \theta}$$

where

τ_{cs} = critical shear stress on the side-slope,

τ_{cb} = critical shear stress on the bed,

ϕ = channel side-slope angle,

θ = the angle of repose of the material that forms the side-slope.

Stevens and Simons (1971), associated the angle of repose to the moment resisting overturning of a riprap particle, as part of their development of a safety factor for riprap design.

Most specifications for riprap shape recommend angular stones, and in addition give ratios for length and breadth of the stone relative to its length. The basic rule for riprap proportion, (Searcy, 1967), which is widely used is that "neither breadth nor thickness of a single stone should be less than one-third its length." In EM-1601, the Corps also requires "not more than 25 percent of the stones, reasonably well distributed throughout

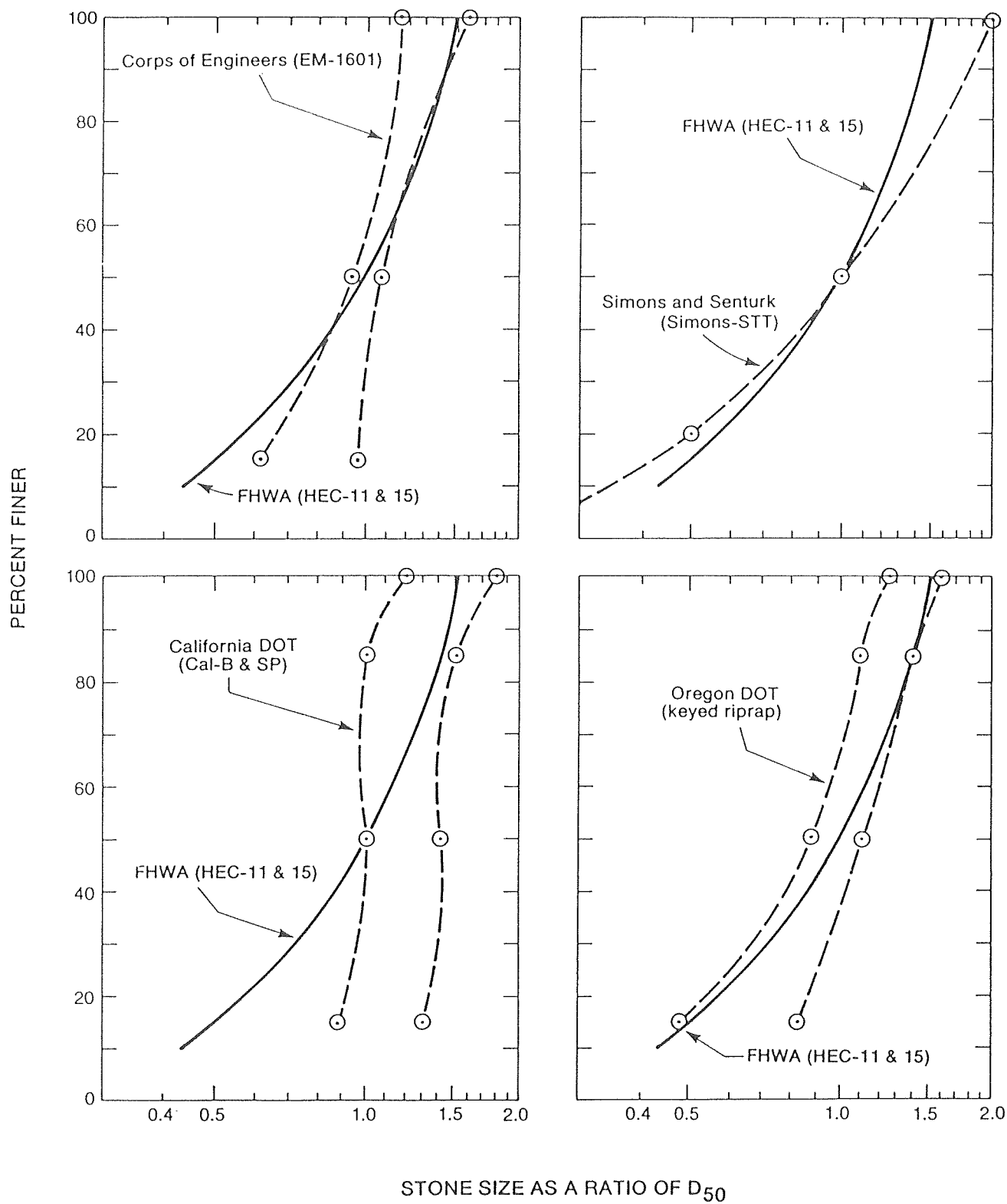


Figure 2. Comparison of Specified Riprap Gradations, Blodgett and McConaughy (1986)

the gradation, shall have a length more than 2.5 times the breadth and thickness."

Thickness

The general rule for riprap thickness is that all stone sizes should be contained within the layer thickness. This results in a thickness equal to the diameter of the largest riprap particles in the distribution. Simons and Senturk (1977), the Corps of Engineers (EM-1601, 1970), Searcy (1967), and others use this rule. Stevens, Simons and Richardson (1984), recommend that in the case of riprap with a large gradation coefficient ($G > 3.0$) that the thickness should be increased to $1.5 D_{100}$ to provide enough material for armor-plating. Maynard (1986) showed increased riprap stability as thickness increased up to $1.5 D_{100}$. The Corps data as presented by Maynard shows that increased riprap thickness decreases the required size.

Highways in the River Environment recommends the riprap thickness should not be less than twelve inches for practical placement, less than the diameter of the upper limit of the D_{100} stone, or less than 1.5 times the diameter of the upper limit D_{50} stone, whichever is greater. If riprap is placed underwater, the thickness should be increased by 50 percent; and if subject to attack by large floating debris or wave action, it should be increased six to twelve inches.

Density

The rock density used to form riprap is a basic factor in riprap stability. However, the variation in density among natural rock types suitable for use as riprap is small. The specific gravity of riprap composed of quartz and feldspathic minerals is 2.65. A minimum specific gravity of 2.5 is often specified.

Durability

The durability of riprap is important both during the transportation of riprap particles from quarry to construction site and during in-service performance. Evaluation of rock durability depends on geotechnical techniques and geologic concepts which include site evaluation, field testing, and laboratory tests. Common laboratory tests include: Los Angeles

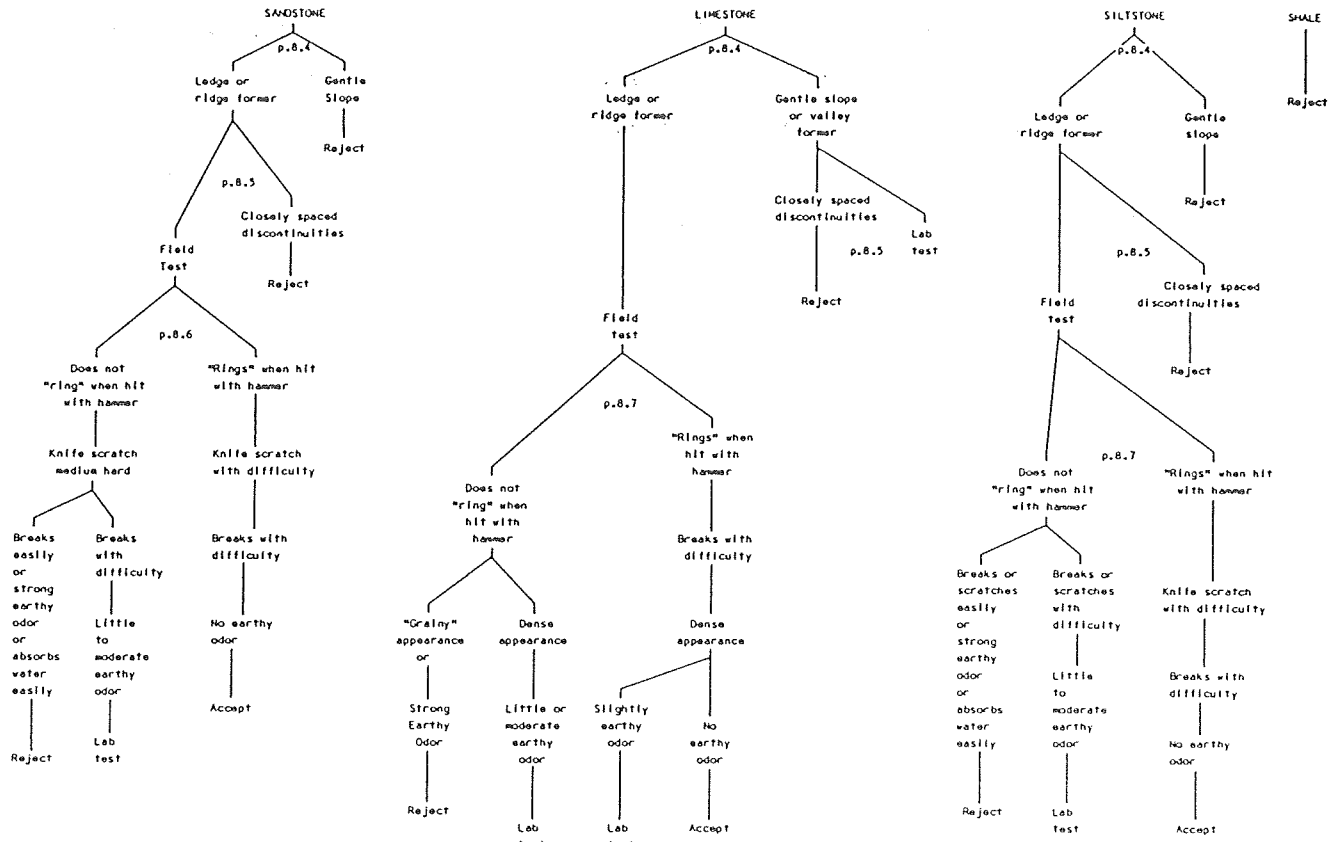
Abrasion, Point-load test, Schmidt hammer, freeze-thaw test, sulfate soundness test, and slake durability-two cycle (ASTM, 1980). Summer and Johnson (1982) devised a rock durability flow chart, which provides a procedure for evaluating rock suitability as riprap for channel lining. This procedure incorporates both site investigation and laboratory testing as required, and is a simple step-by-step approach (Figure 3). Smith, McCauley and Mearns (1970) studied quality control of riprap by the California Division of Highways and recommended the durability absorption ratio (DAR) as the best means of combining the results of inexpensive laboratory tests into an index usable for specifying riprap durability.

Bedding Requirements

The importance of using a filter medium to separate the channel bank material from the overlying riprap gradation has been stressed since the 1940's. Use of a graded rock filter blanket was proposed by Terzaghi (1948) and thoroughly tested by the Corps of Engineers Waterways Experiment Station (1941, 1948). The Terzaghi filter gradation is routinely specified and advocated by some (Posey, 1957) to be the only acceptable filter for permanent riprap installations. However, the cost of producing the Terzaghi filter gradation and the difficulty of installing rock filter blanket has lead to a preference for other filter materials, particularly the synthetic fabrics (Dellaire, 1977).

Since the introduction of synthetic fabrics in the late 1950's, there has been substantial interest in the many possible geotechnical applications of this technology, among which is as a filter medium. Development of design criteria and specifications for geotechnical fabrics has advanced through research by the Corps of Engineers and Federal Highway Administration. Initial research by the Waterways Experiment Station (1972) pointed out that few engineering properties of plastic filter cloth were known at the time, but that good performance had been documented under severe loading conditions. Concern was expressed over the lack of permeability of the fabrics by WES (White, 1982) in their documentation of the performance of filter fabrics in conjunction with bank protection measures. The Federal Highway Administration (Bell and Hicks, 1980) compiled literature and field performance data which resulted in the development of interim criteria and

PART I - SITE INVESTIGATION
(Flow chart may be modified by in-service performance data)
(Page references in this manual)



PART II - LABORATORY TESTS
(reference Phase I report)

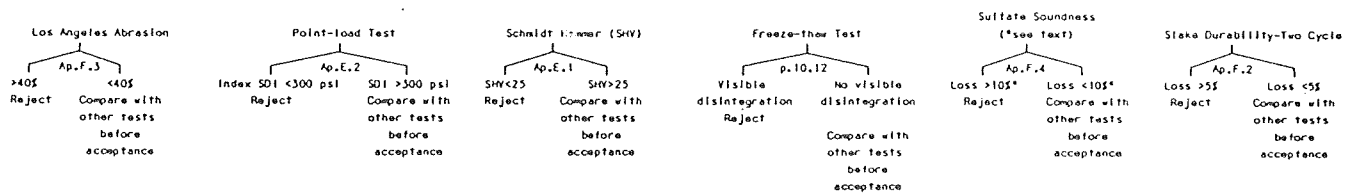


Figure 3. Rock Durability Flow Chart, Summers and Johnson (1982)

specification of fabric properties needed for a wide range of highway applications. Riprap protection is not specifically addressed in this study but related applications such as filtering and separation are pertinent. Christopher (1983) reports on two riprap installations that are over a decade old constructed in 1969 in Florida. This leaves the question of long-term performance of synthetic fabrics still open.

2.3 Hydraulic and Sediment Transport Conditions

The stability of riprap at a site can depend both on the hydraulic forces to which the individual riprap particles are subject and on movement of the channel boundary. The behavior of riprap in a flow field has been studied by a number of researchers. Incipient motion of riprap particles in a uniform flow field has probably been the most widely studied aspect of riprap stability. Nonuniform flow conditions that have been studied include: flow in channel bends and zones of expanding or contracting flow (conditions that are characteristic of flow near bridge abutments, guidebanks, and piers). Movement of the channel boundary can take place due to local scour at piers, abutments and near spurs; or from more general changes due to a change in the sediment transport capacity in the channel reach where the structure is located. The regime of a moveable bed channel and the associated bed-forms can also be an important factor.

Incipient Motion

The flow condition which just sets a solid particle in motion is the primary criteria used in riprap design. Shields (1936) conducted experiments with uniform sediment sizes to develop his well-known incipient motion diagram, which is shown in Figure 4. The Shields diagram is a nondimensional chart with the vertical axis being the ratio of boundary-shear stress to particle weight, and the horizontal axis being the particle Reynolds number. Laboratory data on the incipient motion of nonuniform size distributions has been collected by Gessler (1963) and by Little and Mayer (1972). Gessler (1971) noted that because of fluctuations in turbulence intensity and the nonuniformity of channel bed material, that Shields criteria must be viewed in a probabilistic manner. Shen and Lu (1983) developed a procedure for predicting the final imposition of armoring bed. They found that D_{30} should

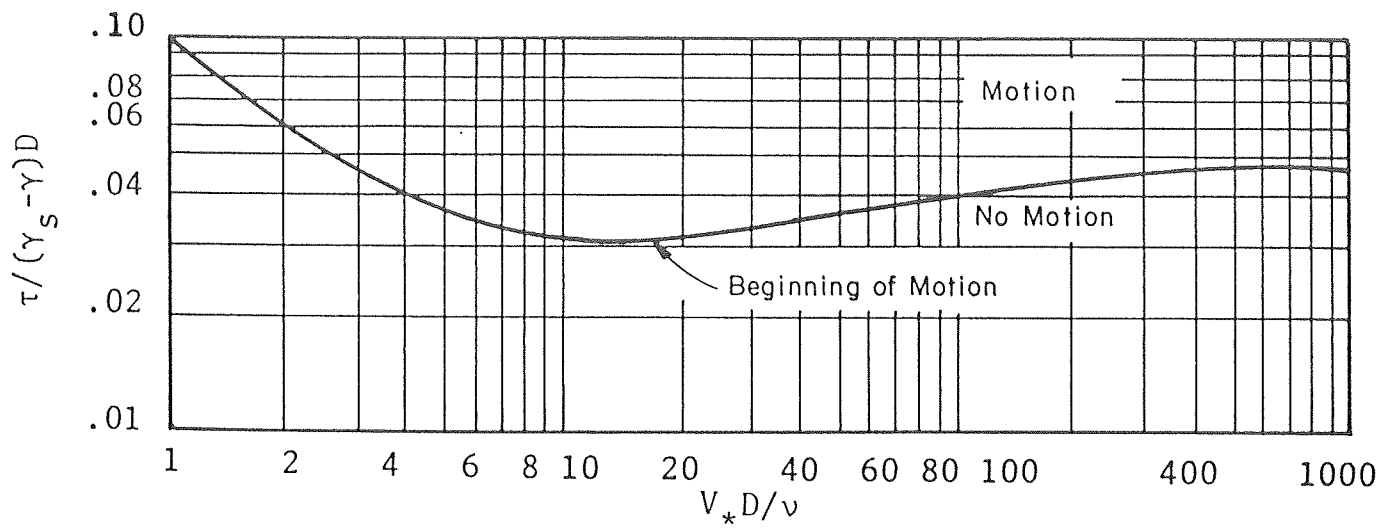


Figure 4. Shields Diagram (after Gessler, 1971)

be used to substitute for the uniform sediment size in the Shields diagram to describe incipient motion.

Most flow conditions associated with riprap design involve fully turbulent flows with the particle Reynolds number in excess of 100, and therefore, it is commonly assumed for design that the Shields Parameter is a constant value. The following table summarized some of the values of the Shields parameter that have been recommended or incorporated into riprap design procedures.

<u>Source</u>	<u>Shields Parameter</u>
Lane (1955)	0.047
Anderson (1970)	0.039
EM-1601 (1970)	0.040
Gessler (1971)	
95% level	0.024
50% level	0.047
Maynord (1978)	0.037
Maynord (1986)	0.033 to 0.040 (depends on thickness)

By combining the Shields criteria, with the Manning equation, and using the Strickler roughness equation, the following relationship can be derived.

$$\frac{D_{50}}{d} = C F^3 \quad (1)$$

where

D_{50} = mean particle size,

C = coefficient as defined below,

d = depth of flow,

F = Froude Number = $\frac{V_a}{\sqrt{gd}}$,

V_a = average velocity,

g = gravitational constant.

Maynord (1978) showed that procedures by Anderson (1970), Li et al (1976), Ramette (1963), Em-1601 (1970), and Isbash (1935) can be closely approximated by the above equation. In general, all these procedures have the same exponent as the above equation, but the coefficient varies for each procedure. Maynord gives coefficient values for straight channels ranging

from 0.22 for bottom riprap (Factor of Safety of 1.0) to 0.33 for riprap placed on a 2:1 bank (Factor of Safety of 2.0). For curved channel sections, Maynard recommends the following equation for determining the C coefficient:

$$C = 0.70 (r/w)^{-0.5} \quad (2)$$

where r = radius of curvature, and
 w = topwidth of the channel.

The C coefficient can be converted to a corresponding value of the Shields parameter, C_s , using the following equation:

$$C_s = \frac{1}{(72.3 * C^{2/3})} \quad (3)$$

Note that large values of C are equivalent to small values of the Shields parameter.

Blodgett and McConaughy (1986) developed a new procedure based on an extensive set of field data. The equation has a dimensional form and is similar to equation (1) but does not explicitly account for flow depth:

$$D_{50} = 0.01 * V_a^{2.44} \quad (4)$$

The equation represents a lower envelope for field sites that had erosion of riprap particles. The authors also evaluate seven design procedures commonly used in highway engineering. Maynard (1986) re-evaluated hydraulic data on riprap stability and has proposed the following equation:

$$\frac{D_{30}}{d} = 0.53 C F^{2.5} \quad (5)$$

The C coefficient was found to vary with total riprap thickness. For a riprap thickness equal to the maximum size in the gradation, and riprap placed on the bed of a straight channel, $C = 0.30$. Additional tests are now under way to determine riprap stability on channel side-slopes and in channel bends.

Boundary Shear Stress

In a flow field, a shear stress is developed at the channel boundary as the flow velocity is reduced to zero at the boundary. If the velocity distribution is known for the flow field, then the boundary shear stress can be determined. For turbulent flow, the velocity fluctuates substantially and results in bursts of shear stress higher than average. The boundary shear stress can be determined for relatively simple flow conditions; but for complex flow conditions, it is seldom calculated directly. For uniform flow conditions, the average boundary shear stress is described by the following equation:

$$\tau = \gamma R S \quad (6)$$

where γ = unit weight of water;

R = hydraulic radius; and,

S = slope of the energy grade line.

Basic research on the distribution of boundary shear stress in straight trapezoidal channels was conducted by Olsen and Florey (1952) and Replogle and Chow (1966). The results of the membrane analysis by Olsen and Florey is widely published in many textbooks and design manuals, and can be used to calculate the distribution of shear stress in a straight trapezoidal channel. In more complicated flow conditions such as bridge crossings, there is less information on the distribution of boundary shear stress. Blodgett (1984) reports that because bridge piers decrease the efficiency of a river section, an increase in the mean velocity of flow takes place through the bridge. The ratio of maximum velocity to mean velocity was reported by Blodgett as increasing by 14 percent in a typical bridge opening.

The velocity distribution in channel bends has been measured and studied by a number of researchers. The equation developed by Rozovskii (1957) is widely used to estimate the magnitude of the traverse velocity component of bend flow. Richardson et al. (1987) in *Highways in the River Environment*, derive an equation for the longitudinal velocity over the width of a stream for a gentle bend of parabolic cross section. Measurements by Ippen et al. (1962) have been widely used as the basis for determining the boundary shear stress in bends in many design procedures (i.e., EM-1602, SCS TR-25, and

Anderson). Improved measurements on boundary shear stress in channel bends with alluvial material were made by Noh and Townsend (1979) using a laser doppler anamometer.

When the channel boundary is free to move, sediment transport processes become important factors in the stability of the river reach. Sediment transport factors are usually referred to by the scale of the phenomena and include local scour, general aggradation/degradation and regional aggradation/degradation. The regime of the flow with sediment transport is also important, since bed forms occur in the channel and will cause displacement of the mean bed elevation. Sediment transport effects govern toedown requirements for channel protection and may lead to additional freeboard. Jones (1984) summarizes various local scour equations associated with bridge crossings. Methods for calculating general scour due to bridge openings are given by Richardson et al. (1987) in *Highways in the River Environment*. Computer models are also used to calculate general scour at bridge openings, several of which are discussed by Holly et al. (1984). A general design procedure for evaluating toedown and freeboard requirements in alluvial channels is given by Simons, Li & Associates, Inc., (1985), which assesses the cumulative effect of bedform height, local scour and general aggradation/degradation.

Posey (1974) conducted a series of tests to evaluate riprap scour protection for bridge piers. Circular and wall pier shapes were studied and in the case of the wall pier shape, the pier was both aligned to the flow and skewed 30 degrees. The piers were protected by graded layers of material, meeting Terzaghi's inverted filter criteria. The flume test was made with a live, sand-bed and during test flows, dunes were the dominant bed form. In selecting the maximum particle size, Posey made the rough estimate that the velocity at the side of the pier was about double the average approach velocity. To protect the area around the pier, the riprap was extended slightly further than the edges of the scour hole that formed without protection. It was found in the degrading conditions, that the protection layer bedded down without losing material at the edges, but some edge settlement was noted during the passage of dunes. Leaching of bed material through the protection did not occur, indicating the utility of the Terzaghi gradation. Posey recommended that piers be protected using a riprap blanket

with an inverted filter gradation placed 1.5 to 2.5 pier diameters in all directions from the face of the pier. A chart for determining riprap size was developed where the size is a function of the shape of the pier, percentage of contraction and the Froude number of the approach flow. Protection of bridge piers was recommended for bridge sites that were experiencing settlement, not as a design procedure for new bridges.

Nece (1974) studied the effectiveness of the Washington State Department of Highways method of preventing scour at bridge piers using riprap. Seven bridge sites were studied and hydraulic data collected. However, all the sites studied were relatively new and had not been subjected to major flood flows.

2.4 Site Characteristics

The location of a bridge crossing can have a significant effect on the methods and extent of stabilization required. Bridges located in an adverse reach of the river such as a channel bend, or a severely braided channel, will encounter dynamic channel conditions. The objective of achieving a stable waterway through the bridge opening may run counter to the fluvial processes underway in the channel. Bridge crossings that are not correctly aligned with prevailing hydraulic conditions in a reach, can encounter severe scour and erosion problems. Blodgett (1986) collected data on the geometric properties of open channels which showed that the geometry of open channels follows a consistent pattern. Detailed measurements by Blodgett on a single channel reach (Pinole Creek at Pinole, California) showed that a channel section can vary significantly over time. This change in channel geometry results in a variation in hydraulic conditions at a structure over time. As Blodgett points out, a survey of a channel section at any given point in time, cannot be taken as providing an absolute definition of the geometric properties of the reach. Rather, it should be viewed as one sample from a population that varies over time.

References that present a general overview of bridge location requirements include: Guide to Bridge Hydraulics (Neill, 1972); "Hydraulic Analysis for the Location and Design of Bridges" (AASHTO, 1982); and, "Highway in the River Environment" (Richardson et al., 1987). These publications place an emphasis on channel response, scour protection, and channel training works.

They provide a guide to hydraulic design in fluvial systems with a particular emphasis on bridge waterways.

One particular aspect of bridge sites that has received increasing attention is the geotechnical aspects of bank erosion. Methods for evaluating the stability of bank slopes are presented in Design of Open Channels (SCS, 1977). Conditions causing slope failure are varied and no single procedure addresses all types of slides. Design of Open Channels addresses rotational slides, and translatory slides. Based on field inspection, Blodgett and McConaughy (1986) identified three types of slides that commonly occur in conjunction with riprap bank protection. Translational slide failures were associated with bank side-slopes that were overly steep; banks that had been undercut by bank degradation or scour; or the presence of excess hydrostatic pressure that reduces the internal frictional resistance of the slope. A modified slump failure is associated with riprap placed near the angle of repose, or loss of support provided by key stones in the riprap matrix resulting in downslope movement of the riprap. The slump slope failure is a rotational slide associated with the formation of fault planes due to nonhomogeneous base material with layers of impermeable material. Causes for slump type failure are: overly steep side-slopes, to the point where the gravitational forces exceed the forces along the friction plane, or excess overburden at the top of the slope.

2.5 River Response

River channels continually adjust to changes in water and sediment discharges in order to maintain a dynamic equilibrium. These adjustments involve changes in channel geometry over a substantial region of the river. These changes in channel form may have significant consequences at a bridge site. Therefore, an analysis of river morphology is necessary to understand the effect of potential changes in regime on geometry and channel pattern. The quasi-equilibrium channel geometry is usually related to slope, discharge and sediment properties (Lane, 1957; Leopold and Maddock, 1958; and Schumm, 1960). These relationships are not continuous and several thresholds have been shown to exist between river patterns (Schumm, 1974). The empirical relationship for river morphology and thresholds are based on laboratory and field data. Lane (1957) and Leopold and Wolman (1957) presented threshold

channel slopes as a function of discharge (mean annual discharge or mean annual flood), separating meandering rivers from steeper braided rivers. Threshold conditions were observed in laboratory studies by Schumm and Khan (1972). The basic threshold for channel formation is the discharge at which bed material movement begins (Schumm, 1974).

Rivers may be classified according to channel pattern or type. The three major patterns have been identified as straight, meandering, and braided (Leopold and Wolman, 1957). Brice and Blodgett (1973) classified alluvial streams into four major types in order of increasing channel slope or bank full discharge, they are: equiwidth point-bar streams; wide bend point-bar streams, braided point-bar streams, and braided streams without point bars. Equiwidth point-bar streams are relatively narrow and deep; the width is not sensitive to changes in channel slope. The widths of the other stream types vary in direct relation to the slope and are sensitive to changes in slope.

Trent and Brown (1984) give a useful procedure for recognizing the potential channel instabilities in conjunction with the design of highways in river environments. They classify factors affecting river stability as natural or accelerated. Accelerated erosion typically results from man's activities in the river system. The procedure requires an understanding of geomorphic processes occurring within the watershed and an awareness of activities affecting river stability.

III. RIPRAP DESIGN REQUIREMENTS

Based on the review of riprap design practice in Arizona and a review of the literature on riprap research, the following design requirements have been found to be essential to conduct a complete design.

3.1 Riprap Properties

The use of the median size of a riprap gradation is being re-evaluated as the characteristic size describing riprap stability. Flume test conducted by the Corps of Engineers show the D_{30} size to be a more reliable predictor of riprap stability. The definition of a characteristic riprap size is key design criteria.

It is important to have a riprap gradation that provides an integrated mass of riprap protection, without voids or large areas of small particle sizes. At the same time, the gradation requirements must be feasible to produce from available quarry sources. The definition of a usable range of riprap gradations and a means of verifying this gradation in the field are important design requirements.

The thickness of a riprap blanket may compensate for small rock sizes. The thickness and gradation go hand-in-hand to produce a competent protection. The thickness is an important design requirement and interdependent with the characteristic size and material gradation.

Use of filter bedding or fabrics is basic design requirement. The Patagonia Case Study raised an interesting question on the performance of filter fabric. The literature search pointed out a similar concern by the Corps of Engineers in some of their field testing of filter fabric.

The durability of rock used as riprap is important both in the transportation and in-place performance of the protection. The Vanar Diversion Case Study, documents the reduction in riprap size during the shipment of riprap. This appears to be a fairly common occurrence and an effect that the designer should take into consideration.

Other design requirements for riprap characteristics which are better understood as to their effect on riprap stability include rock shape and density. It is important that the designers have information on the quality of the material produced by a quarry and some clear rules for evaluating the quality.

3.2 Hydraulic and Sediment Transport Characteristics

The incipient motion criteria for riprap particles is still undergoing fairly extensive research by the Corps of Engineers and Federal Highway Administration. These independent efforts (one based primarily on laboratory tests, and the other on field measurement) are producing similar results. These research programs have superceded most previous research and, therefore, should be the basis for riprap particle stability requirements.

The boundary shear stress is the force that must be resisted by riprap protection. Methods of estimating boundary shear stress are limited to relatively simple hydraulic conditions. The force placed on riprap protection in complex hydraulic conditions, such as channel bends, regions of accelerating/expanding flow, or where a local dissipation of energy occurs (piers and abutments), are more difficult to assess. The determination of boundary shear stress is a very important design requirement.

Degradation of channel beds was common to many of the case histories presented. The degradation problem appears to extend beyond local conditions created by the bridge and involves other activities such as sand and gravel mining, or development encroachment on the river. In developing riprap toedown requirements, degradation producing activities will need to be considered.

The use of riprap at bridge piers to control local scour is a common practice in Arizona and other states. The basis for the design of such protection appears to be quite limited. The procedure is a necessary and cost effective countermeasure for many bridges in degrading channels.

3.3 Site Characteristics

There is a need for the designer of riprap protection to recognize the degree of variation in channel conditions that can take place at a bridge site. As the Case Histories have pointed out, there can be significant variation in channel geometry, alignment and gradient at a site. Within reasonable limits, the designer must anticipate these changes and protect critical components of the site accordingly. The design requirements in this case extend beyond assessing riprap stability at the site into an assessment of river response.

A specific site consideration and design requirement pertaining to riprap is bank stability. An assessment of bank stability should be incorporated into riprap protection design. Detailed geotechnical analysis will not be necessary in most cases, but a qualitative assessment of bank stability should be a basic requirement.

3.4 River Response

An assessment of current river regime and threshold levels should be incorporated into design of riprap protection at a site. Man's activities in the river should be given particular attention. The use of checklists and geomorphic relationships can aid the designer in evaluating river response.

IV. OVERVIEW OF CASE HISTORIES

The development of a set of case histories, documenting riprap performance in Arizona, was the primary objective of Task One. While the focus of the study is on the use of riprap for protection of bridge sites, a comprehensive effort was made to gather case histories from any agency with either research or design experience. Federal, State, County and local agencies were contacted and interviewed over the telephone, and the following questions asked:

1. State the purpose of the study as follows:
We are looking for installations of riprap channel protection, either for bank stabilization or protection of an in-stream structure such as a highway crossing, that have had documented flood flows. Do you know of these type of installations that have been built or are maintained by your agency?
2. If yes, can you tell me where they are located and the projects that the installations were constructed under?
3. Are design plans and calculations available for these projects?
4. Do you have data on flooding that occurred at these installations, or documentation on flood conditions that are on file in your office?
5. Does your agency use a specific methodology for designing riprap protection? If yes, get a manual reference or a copy of the design method.

Based on the initial telephone interview, office visits were scheduled to review in detail documentation of specific projects. Office visits were made to Pima County Department of Transportation, City of Tucson, Soil Conservation Service, and ADOT's headquarters. Recent floods in 1983 caused extensive damage to bridges in Tucson and Pima County. A report was prepared by the Pima County Department of Transportation and Flood Control District that catalogues the damages to public facilities and private property throughout the county. With the assistance of city and county personnel, bridge sites were identified where riprap, gabion, or rock and rail type bank protection had been used for protection of the structure. Construction plans

were retrieved for sites at Swan Road, Rillito River Bridge; 22nd Street, Pantano Wash Bridge; Pantano Wash, North of Speedway Boulevard; and Ajo Way, Santa Cruz River Bridge. Because documentation of 1983 flood damages was extremely limited, none of these sites was selected as case histories for this study.

The Soil Conservation Service sited twelve project locations that might be used as case histories. After reviewing information on file at the SCS, two projects were selected as case histories:

Vanar Wash

Sonoita Creek at Patagonia

It was found that the SCS does not typically have the opportunity to conduct follow up evaluations on project performance. This occurs for a number of reasons, some of which are:

- * Many SCS projects are designed for relatively frequent flooding conditions (25-year flood frequency). Major floods usually cause significant damage resulting in loss of the property, which results in removal of the property from the flood prone area. The SCS project is therefore not repaired since its function no longer exists.
- * The SCS is not an emergency relief agency; and, therefore, they do not gather data on the immediate impacts of flooding.
- * The SCS channel stabilization projects are design oriented, data collection on channel behavior or riprap performance is typically not an objective.

Also, the SCS has undertaken most of their major projects in response to recent major floods. As of yet, these projects have not received any significant floods since their completion. The case histories, that SCS has had an opportunity to prepare, are quite good, particularly the one for Vanar Wash. One drawback, to the use of SCS projects for this study, is that these projects are solely for bank stabilization and flood protection; neither case history has a bridge crossing in the project area.

The primary source of case histories was the bridge maintenance files of the Arizona Department of Transportation. Projects conducted by ADOT include

original Construction at bridge sites, emergency repair projects after flood damage, and on-going projects for repair of scour damage to bridge sites. Because of extensive flooding in 1977, 1978, and 1983, a large number of bridges were damaged. Damage to bank protection also occurred, and at some sites a series of repair projects have been required. With the assistance of the staff of the Hydraulics Group at ADOT, bridge sites were selected from emergency repair projects. These included bridges at the following locations:

- I-19, Santa Cruz River
- I-19, Old Junction Wash
- I-19, Tinaja Wash
- I-19, Agua Fria Canyon
- I-10, Rillito River
- I-19, Esperanza Wash

The need to implement scour protection measures at bridge crossings in Arizona was identified in 1979. In a joint effort by ADOT and FHWA, a multi-disciplinary team of hydraulic, foundation, and structural engineers was formed with the objective of identifying bridge sites with chronic scour problems. The Scour Team initially inspected twenty bridge sites in 1979, and this inspection subsequently resulted in thirteen construction projects at fourteen of the sites. Since initiation of the Scour Team, over one hundred inspections have been conducted resulting in construction projects at 70 sites. Construction funding of countermeasures is budgeted annually, and limits the number of projects that the Scour Team can undertake each year. Through 1985, about \$7.0 million of scour-countermeasure projects were funded by ADOT. Funding on the order of \$1.0 to \$1.5 million per year for bridge countermeasure projects is anticipated by the Structures Section at ADOT.

Case histories were selected from Scour Team Projects that involved riprap protection measures. Information was gathered on projects at the following locations:

- I-17, Deadman Wash
- I-17, New River
- US 89, Granite Creek